Determination of average demagnetizing fields in longitudinal magnetic recording using nanosecond field pulses

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The demagnetizing field across bit transitions in longitudinal recording media is measured quantitatively as a function of linear density using a quasi static write/read tester. Bit transitions with varying linear densities in the range 500–6000 flux changes per mm are recorded on $CoCr_{10}Ta_4$ media films. The media are deposited onto a coplanar waveguide structure, which is used to generate reversal field pulses of well-defined amplitude and 10 ns width to minimize thermally activated processes. The demagnetizing field is extracted from the measured reversal field, which is the sum of the external waveguide field and the internal, density-dependent demagnetizing field. The experimental results are qualitatively consistent with those predicted by a simple magnetostatic model that assumes finite transition widths. © *2000 American Institute of Physics.* [S0003-6951(00)00836-6]

In extremely high-density magnetic recording, linear transition densities may soon exceed 28 000 fc/mm (flux changes per mm).[1,2] The demagnetizing fields across written bit transitions may considerably reduce the energy barrier for magnetization reversal at such densities and thereby increase the sensitivity to thermally activated reversal processes. As a consequence, read-back signal decay as well as transition broadening and percolation may occur, which will ultimately limit the achievable areal density in longitudinal magnetic recording. Direct, quantitative measurements of the demagnetizing fields across bit transitions are difficult, and estimates of their magnitude, so far, have relied mainly on theoretical models.[3] First qualitative experiments were performed by Indeck *et al.* using a spin stand.[4] In this letter we report an experimental method to quantify average demagnetizing fields across bit transitions, by exploiting the linear resolution of a conventional magnetoresistive (MR) read sensor to measure switching fields of media deposited onto a coplanar waveguide.

For infinitely sharp transitions and $\delta \ll B$, where δ is the media thickness and B is the transition spacing, the demagnetizing field H_d in the center of the bit cell is proportional to the transition density $D = B^{-1}$. In most cases, the track width is larger than B and H_d may be approximated by[2]

$$H_d(D) \approx k M_r \delta D. \tag{1}$$

$M_r \delta$ is the remanent areal moment density. The prefactor k is $4/\pi$ for the case of an isolated di-bit[2] and becomes 1 for a square-wave pattern, which is studied here.[5] Equation (1) is expected to be valid for infinitely sharp transitions, in which the finite transition width, characterized by a transition width parameter[3] a, can be ignored. For densities approaching the percolation density[6] $D \propto 1/\pi a$, deviations from the linear dependence are expected and the finite width of a has to be incorporated explicitly into the calculations.

In the present experiments we study magnetic recording media deposited onto coplanar waveguides. Similar structures have been investigated before using the magneto-optical Kerr effect (MOKE).[7] The ''uniform'' magnetization in the presence of short magnetic-field pulses, generated by the waveguide, was detected by Rizzo, Silva, and Kos.[7] Here, we additionally modulate the magnetization by recording bit transition across the waveguide, using a quasistatic write/read tester. The signal amplitude is then monitored as a function of the reverse field by operating this instrument as a scanning magnetoresistive microscope.[8,9] An effective coercivity, determined by the sum of the internal demagnetizing field and the externally applied reverse field, is extracted and compared with respective MOKE measurements. This procedure allows quantitative determination of the demagnetizing field as a function of linear density.

The quasistatic write/read tester has been described before.[9] It uses a merged write/read head placed in physical contact with the sample. Precise and repeatable positioning is accomplished with a $100 \mu m \times 100 \mu m$ piezoelectric $x-y$ stage with a capacitive feedback loop, allowing arbitrary bit patterns to be written. Furthermore, the read portion of the head is used to generate two-dimensional maps of the magnetic stray field patterns of recorded bit transitions.[8,9] Sample heating and high-bandwidth write driver capabilities have recently been exploited to measure field pulse width dependent coercivities over a wide range of parameters, allowing the characterization of thermal stability limits in magnetic recording media.[5,6,10] In the present experiments, a conventional longitudinal MR head with a write gap of 250 nm and a track width of 2.45 μm is used.

The sample is a 25-nm-thick $CoCr_{10}Ta_4$ thin film on a 25-nm-thick Cr underlayer sputtered onto a coplanar wave-

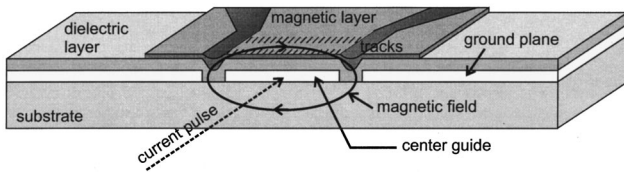[a]Electronic mail: amoser@almaden.ibm.com

FIG. 1. Perspective view of the coplanar waveguide with the magnetic layer. The white areas are the gold layer patterned onto an alumina substrate. In order to increase the current density and, therefore, the maximal available magnetic field, the center guide is narrowed down to 10.6 μm in the area where the tracks are written prior to the application of the magnetic-field pulses.

guide, which has been patterned from a gold layer on an alumina substrate as illustrated in Fig. 1. The waveguide consists of a central conductor of $\approx 10.6\,\mu$m width, which is referred to as the center guide, and two ground planes which are separated by a small gap from the center guide. Launching a current pulse through the waveguide results in a characteristic magnetic-field pulse which is described by the well-known Karlqvist equations, in which the write gap is replaced by the width of the center guide.[11] The present waveguide has an impedance of $Z \approx 60\,\Omega$, a bandwidth of ~ 10 GHz (3 dB point),[11] and is driven by a pulse generator with 200 V maximal amplitude and a rise time of 2 ns. A dielectric layer between the gold and the magnetic layers prevents voltage breakdown. The magnetic $CoCr_{10}Ta_4$ layer has a remanent coercivity of $H_{CR}=80$ kA/m (1040 Oe, measured at ≈ 1 s pulse width) and an areal moment density of $M_r\delta=12$ mA (1.2 memu/cm^2).

Pulse width dependent coercivity measurements were performed employing the quasistatic write/read tester method described before.[5,10] In this method, the dc-magnetized media is exposed to reversed magnetic-field pulses of different widths and amplitudes from the write head. Note that the demagnetizing fields in the resulting dibits reduce the effective magnetic-field pulse amplitude.[10] Using the corrected magnetic-field amplitudes, a stability ratio $K_u V_m/k_B T=345$ and an intrinsic switching field of $H_0 = 98$ kA/m (1230 Oe) was determined. Here, K_u is the uniaxial magnetic anisotropy constant and V_m reflects a median switching volume of the $CoCr_{10}Ta_4$ media. The stability ratio is 2–3 times larger than in modern longitudinal recording media, which is attributed to the relatively large thickness and to incomplete grain isolation in these low coercivity media films. The intrinsic or short time switching field agrees well with that directly measured using the coplanar waveguide and MOKE detection, to be discussed below.

To determine the average demagnetizing field in a bit cell, the difference of the signal amplitude of written bit tracks ΔA is analyzed as a function of the applied magnetic-field pulse amplitude H yielding ΔA vs H curves. Here, the signal amplitude A is defined as the peak value of the power spectrum of the signal at the fundamental frequency. First, ~ 10-μm-long tracks are written into the media across the full width of the center guide using the write element of the head. Then, the read-back signal S_0 of these tracks is acquired with the MR element and the amplitude A_0 is extracted. An example of such a measurement at $D = 1000$ fc/mm linear density ($B=1\,\mu$m transition spacing) is shown in Fig. 2(a) (S_0, solid line). Each valley and each
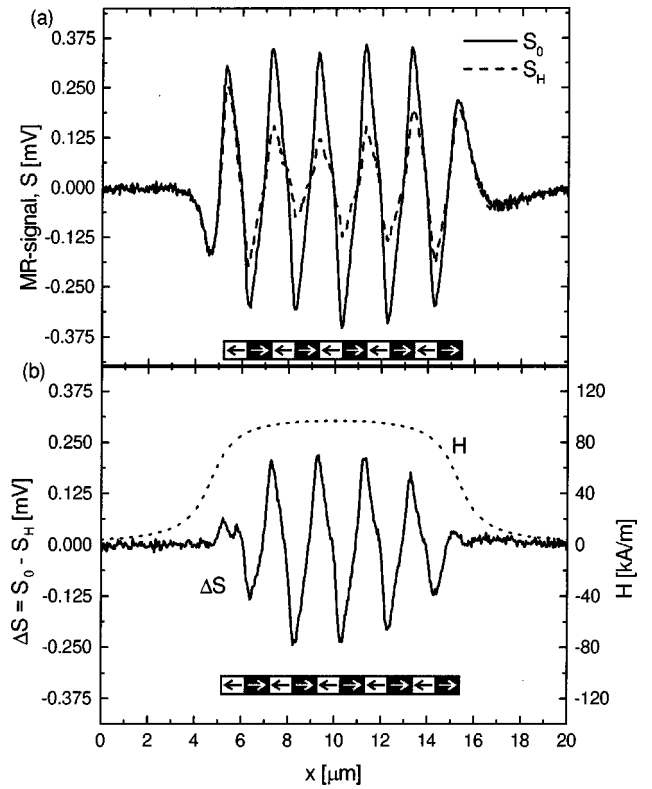

FIG. 2. (a) Read-back signal of a track with a linear density of 1000 fc/mm *before* (S_0, solid line) and *after* (S_H, dotted line) applying a magnetic-field pulse H from the waveguide. (b) Difference of the read-back signals (solid line) in (a) and the magnetic-field amplitude calculated from the Karlqvist equations (dotted line).

peak correspond to an individual bit transition. The reduction in read-back signal at the edges of the center guide is attributed to a slightly larger distance between the read element and the film surface at those locations, caused by an uneven topography near the gaps between the center guide and the ground planes (see Fig. 1). After exposure to a 10-ns-long magnetic-field pulse with an amplitude of 97 kA/m (1210 Oe), the read-back signal is reexamined [S_H, dotted line in Fig. 2(a)] and the amplitude A_H *after* the H pulse is determined. Clearly, a reduction of the signal is observed while the transition positions are preserved. Note that at these short time scales (10 ns), the effect of thermal activation processes is minimized and nucleation of the reversal process occurs only in those regions where the total magnetic reversal field exceeds the local switching field.

Figure 2(b) shows the difference signal $\Delta S=S_0-S_H$. The amplitude of the in-plane component of the waveguide field, as calculated using Karlqvist's equations, is also shown (dotted line). It is largest in the middle of the center guide and decays toward the edges. We confine the analysis to the homogeneous portion in the center of the waveguide, where the field variation is less than 5%.

Remanence loops ΔA vs H are acquired for a given pulse duration by monitoring the difference signal amplitude $\Delta A=A_0-A_H$ as a function of the magnetic field supplied by the waveguide. Figure 3 shows the normalized amplitude difference, $1-2\Delta A/A_0$, as a function of H for different linear densities and a pulse duration of 10 ns. We define the magnetic field H_{CR}^* required to achieve $\Delta A=A_0/2$ as the density-dependent effective remanent coercivity. At low
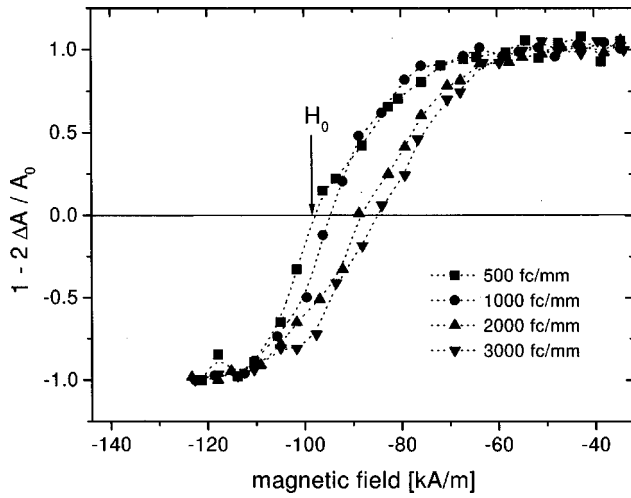
FIG. 3. Remanent normalized difference signal ΔA vs H loops as a function of the linear transition density (magnetic-field range -1800 to -400 Oe). For higher linear densities the loops shift to lower fields as a result of the increasing demagnetization field. The arrow points to the fitted intrinsic switching field H_0 from the dynamic coercivity measurements.

transition densities (500 fc/mm), H_{CR}^* agrees well with the MOKE measurements of $H_{CR} = 94$ kA/m (1180 Oe).[7,12] At higher densities, the effective remanent coercivity H_{CR}^* is reduced by the additional, density-dependent demagnetizing field $H_d(D)$ according to the relation $H_{CR}^*(D) = H_{CR} - H_d(D)$.

The effective remanent coercivity is plotted as a function of the linear density D in Fig. 4. H_{CR}^* decreases roughly linearly with D for low transition densities. Beyond ≈ 3000 fc/mm, no further decrease of H_{CR}^* is observed. We can, therefore, write $H_{CR}^* = sD + H_{CR}$ at low linear densities $D < D_s$ and $H_{CR}^* = sD_s + H_{CR} = $ constant otherwise, where D_s is the position of a shoulder, above which H_{CR}^* is constant. A least-squares fit of this function to the experimental H_{CR}^* data yields an offset of $H_{CR}(\tau = 10$ ns$) = 98 \pm 1.6$ kA/m (1224 ± 20 Oe), a slope of $s = -4.4 \pm 0.8$ mA [$(-5.5 \pm 1.0) \times 10^{-3}$ Oe cm], and a shoulder at $D_s = 2940 \pm 370$ fc/mm. Note that the present fit is about 3.5 times better than a simple linear fit without a shoulder.
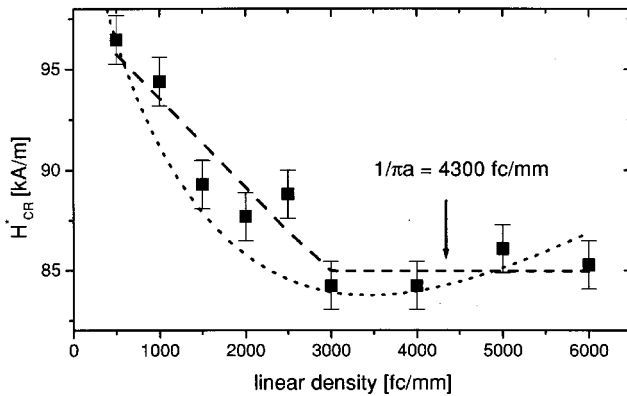

FIG. 4. Remanent coercivity H_{CR}^* as a function of the linear density, D (remanent coercivity range 1025–1225 Oe). The dashed line is a fit to the experimental H_{CR}^* data using infinitely sharp transitions. The dotted line represents the demagnetization field averaged across the bit cell using a finite transition parameter $a = 74$ nm (percolation density $1/\pi a \simeq 4300$ fc/mm).

The shoulder occurs well below the percolation density $1/\pi a \simeq 4300$ fc/mm, in which the transition parameter $a = 74 \pm 10$ nm is estimated from the Williams–Comstock model using the present media parameters and an estimated head media spacing of ~ 80 nm.[13] Substituting the relation between bit-averaged demagnetizing field and the effective remanent coercivity $H_d(D) = H_{CR} - H_{CR}^*(D)$ into Eq. (1) and using s from the above fit, $k = s/M_r = 0.39 \pm 0.07$ is obtained. This experimentally derived prefactor k is about 2–3 times smaller than the expected value of 1 for infinitely sharp transitions [Eq. (1)].

A more accurate analysis of the data may be obtained by including the finite transition width parameter $a = 74$ nm in the calculation of H_d. If the magnetization change in a transition assumes an arctangent form, the magnetic field along the center line of the recording medium may be calculated analytically.[3] Using such an analytic expression we have calculated the demagnetizing field averaged between two neighboring transitions and included the result in Fig. 4 as the dotted line. We note that averaging the demagnetizing field in a bit cell masks details of the spatially dependent demagnetizing fields and the temporal dependence of switching processes. For example, a more elaborate model would consider switching rates that are exponentially dependent on the total applied magnetic field.[14] Since demagnetizing fields vary spatially in a bit cell, position-dependent switching probabilities and the nonlinear response function of the read head would have to be taken into account in a more accurate model.

A method to measure average demagnetizing fields in longitudinal magnetic recording media has been presented. An important advantage of this method is that the magnetic-field amplitude is given only by the physical design of the waveguide and the transmitted current, which may be accurately measured. In addition, well-defined pulses of varying widths may be applied. On the downside, the fabrication of the samples involves several lithographic steps as well as the deposition of the recording media on top of the waveguides, restricting the method to relatively few selected cases.

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